Micro Patterning of Organic Solvents on OLED Device Using EHD Inkjet Technology

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ABSTRACT

Although there are many modes of the ejection mechanism from the EHD nozzle [2], a cone-jet mode, a pulse-jet mode and a micro-dripping mode have been analyzed by capturing the jetting phenomena using organic solvents as working fluids in this study to find out the optimum liquid for each mode at the required condition. The detailed jetting mechanisms and modes have been investigated to design the EHD jetting system optimally and to examine forces on the jetting mechanism for droplet-on-demand operation according to important physical parameters such as an onset voltage, liquid conductivity, surface tension, viscosity, etc. The effect of the factors has been analyzed by the experiments initially to confirm the dominant factors for the determination of the width of the patterned line, which should be less than 100μm. Then, the modeling equation has been derived to calculate the jetting mechanism numerically using those important factors and to compare with the experimental results of the micro-sized patterning. The EML (EMission Layer) of the OLED (Organic Light Emitting Diodes) device has been calculated numerically by the confirmed equation and fabricated experimentally by the developed micro patterning technology using the EHD inkjet system in this study.

Keywords: electrohydrodynamic, inkjet, patterning, solvent

1 INTRODUCTION

Formation of micro and nanometer size droplets from an electrostatic nozzle is an important problem. It is useful in a number of different fields including inkjet printing, electrospray mass spectroscopy and processing of biomaterials, electrohydrodynamic atomization, and other applications. This process can be considered as a branch of fluid mechanics concerned with electrical force effects. The variety of variables affecting electrohydrodynamic ejection often makes it difficult to investigate and predict its operation, for instance, the difficulty in getting an exact formulation of the dependence of droplet size with other parameters such as applied voltage, flow rate of solution, size of capillary nozzle, electrode configuration and properties of liquid like viscosity, electric conductivity, relative permittivity, and surface tension. Among these effects, the electrospray can be classified in many modes such as dripping, micro-dripping, pulsating, cone-jet and instability of cone-jet including varicose, kink and multi-jet. This classification is important to consider and define main factors (main variables) in establishment of controlling equation of droplet size. However, detailed analysis of the transition dynamics of this process is still lacking.

According to above classification, onset voltages which can be defined as a threshold voltage for transferring from the dripping mode to the pulsating mode and a threshold voltage resulting in the stable cone jet are obviously important parameters because they can be used to analyze the control of droplet size and the emission regimes corresponding to the experimental configuration. Hence, the electrospray can be applied for various fields such as the stable cone-jet regime which is relevant to the production of macromolecular ions and is used in conjunction with mass spectrometry in fundamental research involving biological molecules, and other regimes can be used in electrostatic painting, drug delivery, drug micro-encapsulation, etc.

In this study, the EHD inkjet experiments were carried out using several organic solvents to find out the optimum solvent for the OLED device which was made by the EHD patterning.

2 EXPERIMENTAL METHOD

2.1 Selection of organic solvent

There are many organic solvents for the display device, and their viscosity and dielectric constant are important factors for the EHD inkjet. Four useful organic solvents such as a Dichloromethane (DCM), a Dichlorobenzene (DCB), a Dichloroethane (DCE) and an Acetonitrile (ACN) as shown Table 1 were tested for the EHD inkjet system.

The DCM has lower dielectric constant and viscosity compared with the DCB. The ACN has the highest dielectric constant among four organic solvents while the DCM shows the lowest viscosity. Thus, the experiments were performed using each of four organic solvents.

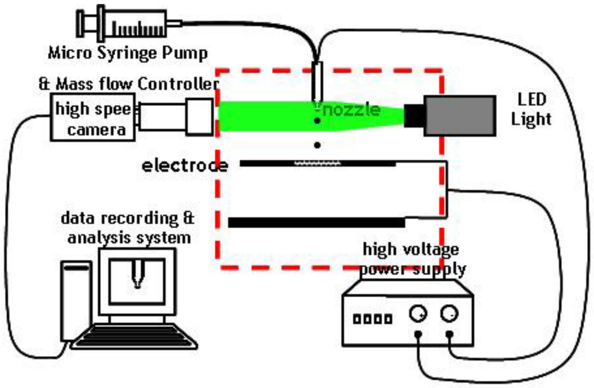
Table 1 : Properties of Organic Solvents

(a) Dichloromethane, Dichlorobenzene

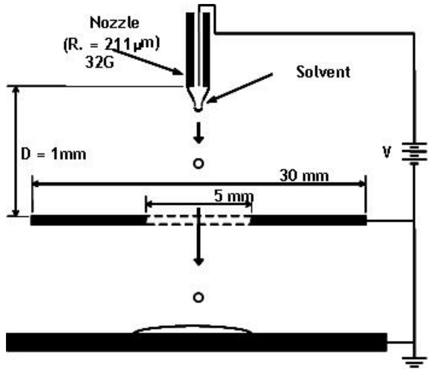
	Dichloromethane	1,2-Dichlorobenzene
Boiling point (°C)	40	180
Density (g/cm^3)	1.33266 (at 20°C)	1.3059 (at 20°C)
Surface tension (mN/m)	27.2 (at 20°C)	26.84 (at 20°C)
Dielectric constant	**8.93 (at 20°C)**	**10.12 (at 20°C)**
Viscosity (mPa·s)	**0.413 (at 25°C)**	**1.32 (at 25°C)**
Vapor pressure(kPa)	58.2 (at 25°C)	0.18 (at 25°C)
Dipole moment (D)	1.6	2.5
Bezene	?	5
Ionization potential (eV)	11.32	9.08

(b) Dichloroethane, Acetonitrile

	1,2-Dichloroethane	Acetonitrile
Boiling point (°C)	83.5	81.6
Density (g/cm^3)	1.2351 (at 20°C)	0.7857 (at 20°C)
Surface tension (mN/m)	31.86 (at 25°C)	28.66 (at 25°C)
Dielectric constant	**10.42 (at 20°C)**	**36.64 (at 20°C)**
Viscosity (mPa·s)	**0.779 (at 25°C)**	**0.369 (at 25°C)**
Vapor pressure(kPa)	10.6 (at 25°C)	11.9 (at 25°C)
Dipole moment (D)	1.8	3.924
Bezene	3	5
Ionization potential (eV)	11.04	12.19



(a) Overview

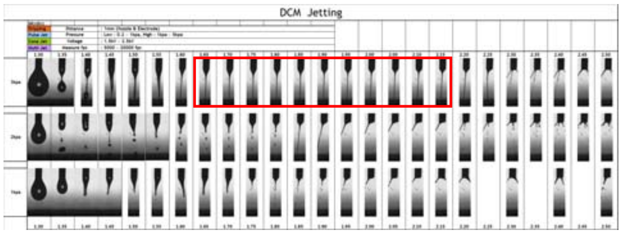


(b) Test section

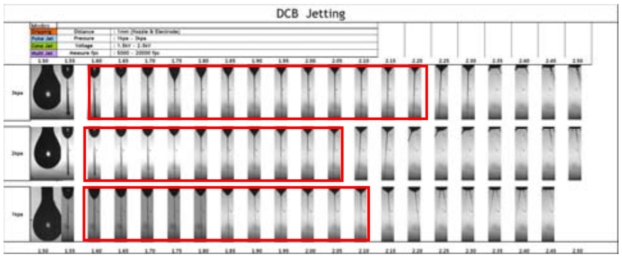
Figure 1 : Experimental set up for EHD inkjet

2.2. Experimental Setup

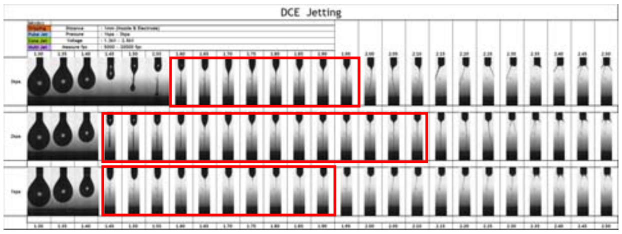
The droplet and jet were formed and ejected from a micro glass capillary tube with an outside diameter of 211μm including a pole made of Pt wire, an electroplate with a hole of 5mm at the center, and the distance between the nozzle and electrode plate of 0.5mm as shown Fig. 1. Images of droplet ejection were captured by a high-speed camera (IDT XS-4) 512 × 512 pixel resolution with a micro-zoom lens (infinity K2), and a 6 W LED lamp. A high-voltage power supply system with maximum voltage of 10.0 kV was used to control the electrostatic field and liquids were supplied into the glass capillary by a micro-syringe pump. The liquids used in this experiment were four organic solvents as shown in Table 1. The applied voltage changed from 1.5kV to 3kV at the pressure of the syringe pump of 1kPa to 3kPa.



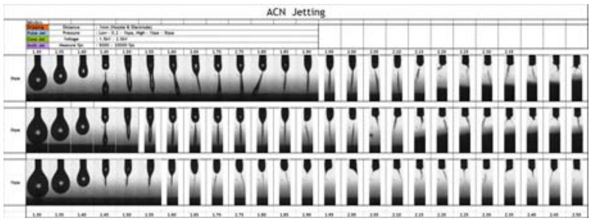
(a) Dichloromethane (DCM)



(b) Dichlorobenzene (DCB)



(c) Dichloroethane (DCE)



(d) Acetonitrile (ACN)

Figure 2 : Jetting performance of organic solvents

3 RESULTS AND DISCUSSION

3.1. Jetting of organic solvents

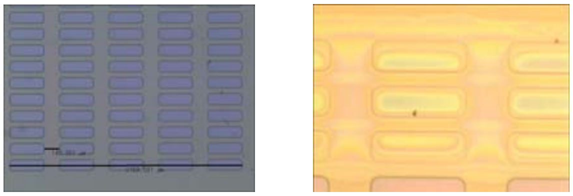
Jetting formations depends on the static pressure and the applied voltage as shown in Fig. 2. Although several jetting modes such as a dripping mode, a pulse jet mode, a cone-jet mode and a multi-jet mode were observed, the cone-jet mode was confirmed for the good performance for the jetting and patterning by the EHD inkjet system. Therefore, a red box was inserted in Fig. 2 to show the stable cone-jet mode.

Among four solvents, the DCB showed the best jetting performance. The DCM did not have the stable jetting at the pressure of 1kPa and 2kPa. Only for 3kPa, the good performance was observed between 1.65kV and 2.15kV. Although the DCE showed the good jetting performance, the range of the stable jetting was smaller than that of the DCB. The stable jetting range was not observed for the ACN. Thus, the DCB was selected for the patterning experiments.

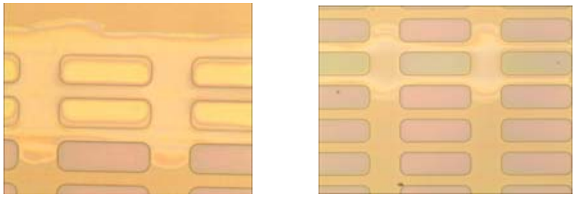
3.2. Patterning on pixel device

The line patterning was applied for the OLED device with many pixels. The size of each pixel was 300µm X 100µm as shown in Fig. 3 (a). One patterned line should be printed inside one pixel.

Firstly, the pixel height was overflowed by the ink and three pixels were wet on the device because the mass flow rate was high as shown in Fig. 3 (b). Thus, the constant pressure was reduced to 0.8kPa to decrease the mass flow rate. However, two lines of the pixel were still wet as shown in Fig. 3 (c). Then, the constant pressure was reduced again to 0.5kPa and the ink was printed on the device as shown in Fig. 3 (d). Finally, the line was printed in one pixel and the ink did not overflow.



(a) OLED pixel (b) 90µm, 20mm , P = 1kpa



(c) 90µm, 20mm/s, P = 0.8kpa (d) 90µm, 20mm, P = 0.5kpa

Figure 3 : Pixel Patterning on OLED device by EHD

3.3. Numerical Analysis Methods

The force balance of the electrohydrodynamic inkjet consis of gravitational force, surface tension force and electrostatic force. That force balance equation can be expressed by

$$F_{st} = F_e + F_g \tag{1}$$

where, F_{st} is surface tension force, F_g is gravitational force and F_e is electrostatic force.

The onset voltage is defined as the applied voltage where the dripping mode for ejection of droplet from electrostatic nozzle transfers to pulsating cone-jet mode or other modes. The equation for calculation of onset voltage can be built based on the competition between electric force and surface tension force. The magnitude of the normal electric field in configuration between the capillary and the earthed electrode can be calculated as follows [1]:

$$E_n = \frac{\sqrt{2}U}{r\ln(\frac{4D}{r})} \tag{2}$$

where U is the applied voltage, r is the outer radius of the capillary, and D is the distance between the nozzle tip and the earthed electrode plate. Hence, the normal electric force around a pendant drop on the electrostatic nozzle tip in the non-uniform electric field is formulated as

$$F_e = \frac{1}{2}S\varepsilon_n^2 = \frac{1}{2}\theta\varepsilon_0\frac{U^2}{\ln^2(\frac{4D}{r})} \tag{3}$$

The surface area of the pendant droplet can be approximated by the outer radius of the nozzle tip r as $S = (1/2)r^2\theta$. Thus, the electric force acting on the pendant droplet is a function of the applied voltage, the distance between the nozzle tip and the earthed electrode plate D and the outer radius of the capillary.

The surface force due to the surface tension γ t of the liquid in ambient air is also approximated with the assumption that the radius of curvature of the droplet equals the outer radius of the capillary nozzle. It can be calculated as follows :

$$F_{st} = 2\pi r\gamma\varphi \tag{4}$$

where φ is Harkins correction factor [2] that depends on the ratio of the radius of the nozzle and the capillary length. The oscillation of the meniscus starts since the electric force approaches the surface force, then, the onset voltage can be established. Combining Eqs. (3) and (4), the onset voltage can be expressed as

$$U_{ons1} = \sqrt{\frac{r\gamma\varphi}{2\varepsilon_0}} \ln(\frac{4D}{r}) \tag{5}$$

Equation (5) is used to calculate the onset voltage at which the dripping mode stops. Furthermore, if the voltage increases, the pulsating regimes will stop and the stable cone-jet mode will occur. Thus, another threshold voltage appears at which the transition from the pulsating regimes to the stable cone-jet mode is observed. In this model the onset field at the tip of the hyperboloid surface is also defined as the equilibrium between the electrical stress pulling the liquid toward the electrode and the surface tension pulling the liquid back to the needle [3,4]. Assuming that once the onset voltage in the needle-type emitter is reached, the liquid snaps-over to a Taylor cone and jet emission starts. This voltage can be calculated by the following equation.

$$U_{ons2} = \sqrt{\frac{r\gamma}{\varepsilon_0}} \ln(\frac{\beta D}{r}) \tag{6}$$

where the shape factor β is form 2 to 4.

4 CONCLUSION

The optimum dielectric constant and viscosity should be required for the stable jetting of the organic solvents. The wetting phenomena for overflowing on the nozzle were observed by high dielectric constant. The dielectric constant is an important factor for the ink which is ejected from the EHD nozzle by the electric force. However, if the ink has higher dielectric constant than the threshold value, the ejection becomes unstable like the ACN. The stable jetting also depended on the meniscus height from the nozzle, which was determined by the applied voltage. The thickness of the jet was also controlled by the applied voltage although the unstable jetting was observed by high voltage. Thus, the optimized voltage should be determined. The DCB showed the most stable jetting among four organic solvents such as DCM, DCB, DCE, ACN by the jetting experiments.

A new equation was derived and confirmed in this study to calculate the onset voltage accurately by various parameters. The calculated results of the proposed model show good agreement with the experimental results. Nevertheless, more experiments and analyses are required in order to confirm the developed equation exactly with the factors in physical effects on the ejection of the droplets.

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